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OBSERVATIONS FROM THE EEFIT-TDMRC MISSION TO SULAWESI, INDONESIA TO INVESTIGATE THE 28TH SEPTEMBER 2018 CENTRAL SULAWESI EARTHQUAKE

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Abstract: *On the 28th September 2018 at 17:02 local time, an earthquake of magnitude 7.5 M_w hit Indonesia, with epicentre located 78km north of the city of Palu on Sulawesi Island. The earthquake ground shaking triggered four substantial landslides and several instances of liquefaction and land subsidence. Furthermore, a localised tsunami was triggered in Palu Bay, likely due to subsea landsliding. These hazards caused damage to over 70,000 properties and the deaths of at least 4,438 people. The UK Earthquake Engineering Field Investigation Team (EEFIT) and Indonesian Tsunami and Disaster Mitigation Research Centre (TDMRC) conducted a joint reconnaissance mission to areas affected by the earthquake. This paper presents their main findings regarding these multiple hazards and their impacts on the built environment.*

Introduction

On the 28th September 2018 at 17:02 local time, an earthquake of magnitude 7.5 M_w hit Indonesia, with epicentre located 78km north of the city of Palu on Sulawesi Island. The consequent earthquake ground shaking caused significant damage to buildings and infrastructure and triggered extensive ground failures in areas of Palu. The earthquake was followed by a tsunami, that also caused devastation to the Sulawesi coastline, in particular to Palu bay and Donggala town. According to the Central Sulawesi Administration (as reported in the Response Update Brief, 2019), as of the 30 January 2019, the event caused 4,340 fatalities (including 667 missing), 4,438 people sustained major injuries, 42,864 buildings were damaged, and 164,626 people have been displaced from their homes. Furthermore, 2,546 classrooms were damaged or destroyed.

Immediately after an earthquake and/or tsunami, there is a unique opportunity to gather information on the performance of buildings and infrastructure, and on the impact of disasters on communities. This paper presents a summary of the field observations made during a reconnaissance of areas affected by the 28th September Sulawesi event. The reconnaissance took place between the 17-23rd November 2018 and was conducted jointly by EEFIT and the Tsunami and Disaster Mitigation Research Centre (TDMRC) of Banda Aceh, Indonesia.

Geotechnical Investigation

Fault Surface Rupture Investigation

The total fault rupture length along the Palu-Koro Fault was more than 140km with a calculated mean displacement of 3-5m (Valkniotis, 2018). Pre-mission information suggested that surface

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rupture of the fault had occurred with the fault having been mapped using satellite imagery and co-seismic displacement analysis by Valkniotis, (2018).

Part of the mission was focussed on ground-proofing the fault rupture (Figure 1) and surface rupture of the fault was observed in the field with evidence of displacement identified at the Palu city bay-front area and at the far southern end of the Palu valley. Other instances of surface fault rupture were identified on the western side of the Gulf of Palu at Tasiburi as well as on the eastern side of the bay near Dalaka. However, the interconnectivity of these ruptures with the surface rupture in the Palu valley area is inferred, particularly the undersea component.

Numerous expressions of the fault surface rupture were identified throughout the area, typically by the offset of linear features such as roads (Figure 2), but also dramatic continuous surface ruptures through agricultural land. Left-lateral strike-slip displacement was measured by the Team to be a maximum of 5m at Pewunu (Figure 3), and typically between 3-4m. It is possible that, as the Pewunu area is in close proximity to the valley sides and steep terrain, the soil is thinner and thus the greater displacements in the bedrock are more closely represented at the surface.

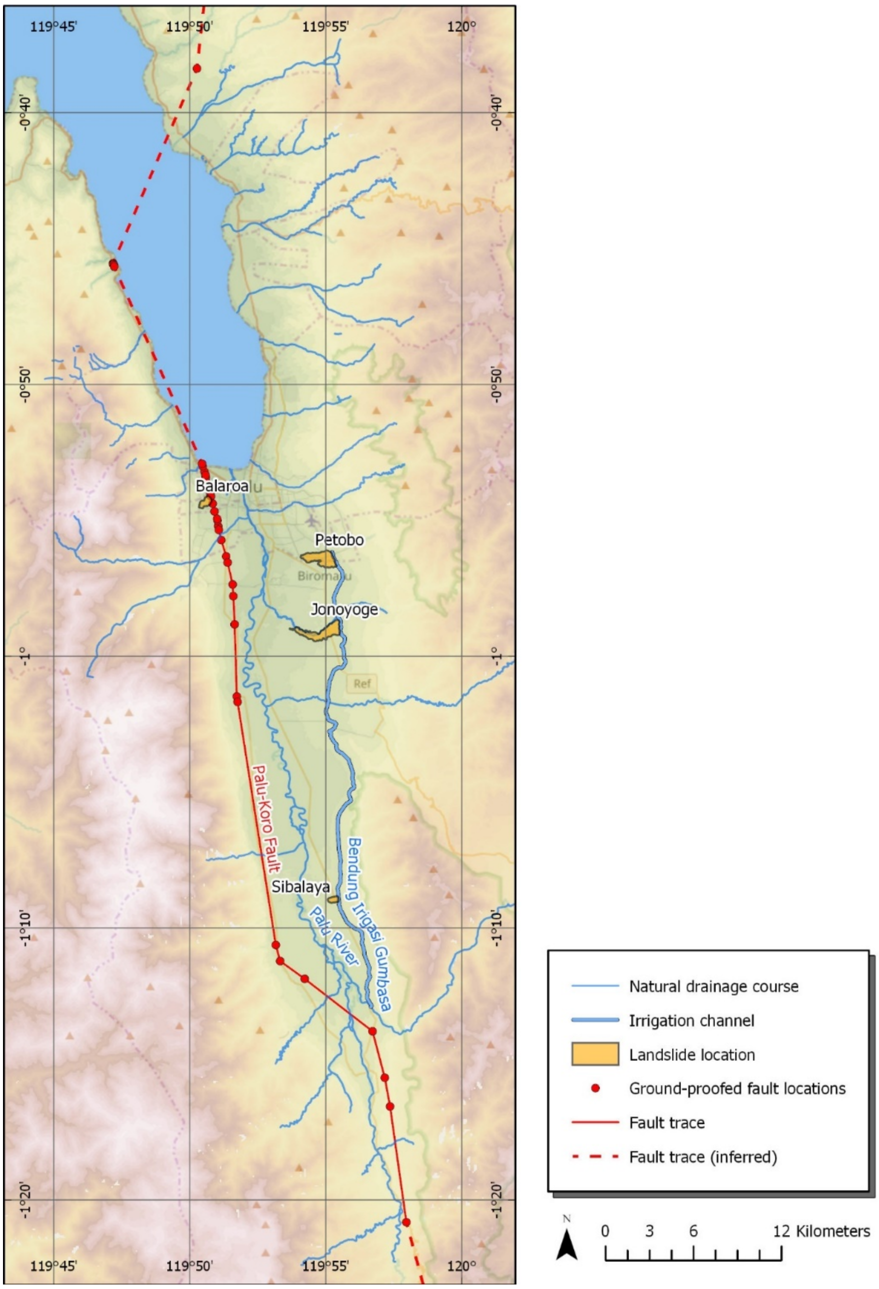

Figure 1. Overview of Palu valley showing the Palu-Koro Fault, major landslides, Bendung Irigasi Gumbasa irrigation channel and the major natural drainage courses.

Figure 2. Offset road due to strike-slip fault displacement.

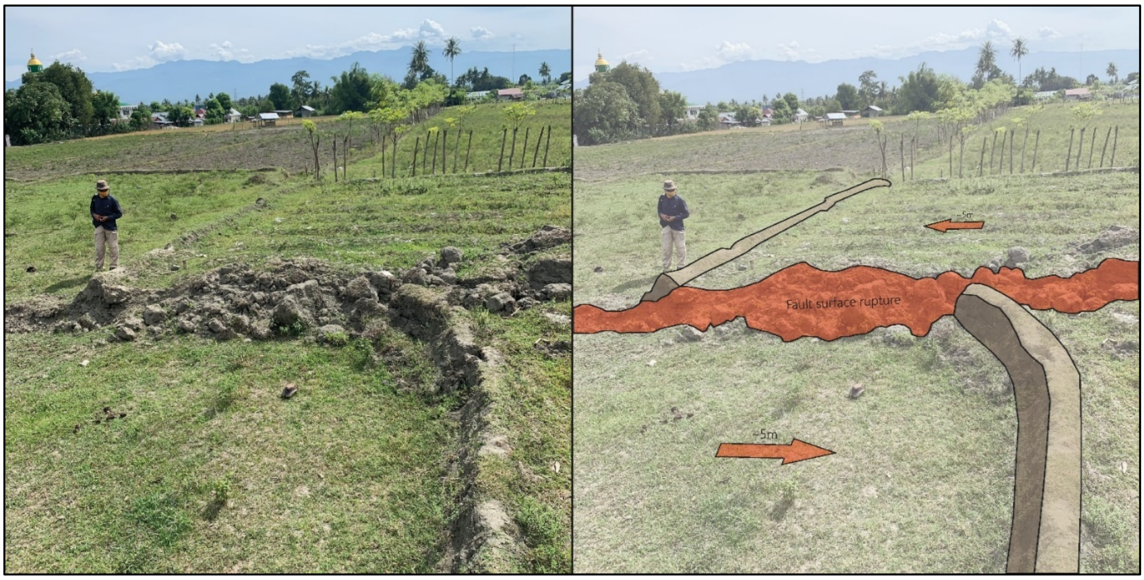

Figure 3. Displacement of approximately 5m along fault surface rupture shown due to offset rice paddy terraces.

Landslide Investigation

The three main landslides that occurred following the earthquake are considered to be low-angle liquefaction-induced debris flows that were extremely mobile due to significant water content. The causal factors are largely thought to be related to the hydrogeological regimes' interaction with the topography as well as possible anthropogenic factors. Most notably, a man-made irrigation channel running along the eastern side of the valley (Figure 1) appears to be the initiation point of the two largest landslides with evidence suggesting the underlying hydrogeological regime is significant affected by its presence (Figure 4). Whether or not the irrigation channel alone directly led to the failures is cause for discussion, but it is likely at the very least that it contributed to the long runouts due to the significant volume of additional water introduced into the ground.

Further investigation is needed to establish a clearer picture of the landslide causes and mechanisms, ideally with some detailed intrusive geotechnical investigation. This will provide information on which to design potential mitigation options, such as drainage infrastructure and modifications to irrigation systems.

Figure 4. Difference in vegetation growth due to groundwater conditions on either side of the Bendung Irigasi Gumbasa. Green vegetation growth (left) indicates wetter ground conditions as opposed to brown land with lack of vegetation growth (right) indicating mostly dry ground.

Liquefaction Investigation

In the aftermath of the earthquake, the media widely reported liquefaction as a significant cause of damage. However, the associated descriptions of the effects – complete burial of towns – was not consistent with conventional understanding of liquefaction induced damage. Field observations by the EEFIT-TDMRC team identified the large-scale mass movement events as liquefaction-induced landslides. Two other manifestations of ground failure were also observed that are more consistent with typical liquefaction occurrence:

- "Conventional", localised liquefaction-induced settlements and tilting of individual structures, with associated ejecta features (Figure 5). These seemed to affect a small number of isolated areas.
- Liquefaction of seafront areas near estuary mouths, resulting in significant areas of land mass slumping into Palu Bay (Figure 6). The Team identified areas on both sides of Palu Bay affected by this. It is possible that some of the reported coastal inundations were caused by backwash over these slumps.

Examples of 'conventional' liquefaction were rather localised and many similar structures in a given area had differing amounts damage. It may be that ground shaking very close to the fault was notably stronger, such that only soils above the fault experienced sufficiently strong shear stresses to liquefy. More likely is that the sandy soils across Palu are largely medium dense to dense – this information was noted by Dr Sukiman Nudin at Tadulako University - and as such far less likely to experience liquefaction. The suggestion is corroborated in part by data collected by Thein et al. (2014) as part of their micro-tremor study of the city's soils.

The team identified areas on both sides of Palu Bay affected by seafront loss due to liquefaction. The EEFIT-TDMRC observed this at Loli Tasiburi on the Western shore and at Lero on the Eastern coast. Locals at Loli Tasiburi reported that large areas of coastline had broken off and fallen into the sea, with one indicating Palu, visible in the distance around a headland, which he reported had previously been obscured by the land. An eyewitness described the soil "bubbling", and two large upwards spurts of water on the beach. The soil type and inevitable high groundwater level suggest liquefaction was a clear possibility, and the eyewitness reports are consistent with soil liquefying. The team concluded that liquefaction had therefore occurred in the coastal soil, and either the resultant large settlements were sufficient to submerge the coastal land or (more likely) lateral spreading has taken the shoreline into the bay.

Figure 5. Damage to a one-storey building in Lasoso due to differential settlement induced by liquefaction. Sandy ejecta in garden.

Figure 6. Area of land lost to coastal slumping due to liquefaction at Lero.

Tsunami Investigation

As mentioned above, the 28th September 2018 earthquake had a predominantly strike-slip mechanism. The relative movements of the plates in this type of earthquake are largely horizontal, and hence would not typically cause a tsunami, though due to the steep bathymetry of the bay (Figure 7) it is not inconceivable that horizontal movement could displace water (STEER, 2019). Measurements from outside of the bay suggest that a tsunami originating from a location close to the epicentre would not have had time to reach the bay before the first waves were observed (Muhari *et al*., 2018). There are a variety of causal mechanisms now suggested, amongst which are landslides triggered by the earthquake. This seems plausible given the number of observed sub-aerial landslides that occurred and some slides on the west of the bay that were seen to cause tsunamis (STEER, 2019). However, to date the location of a single submarine landslide of the size required to cause a tsunami of the size recorded has not been identified.

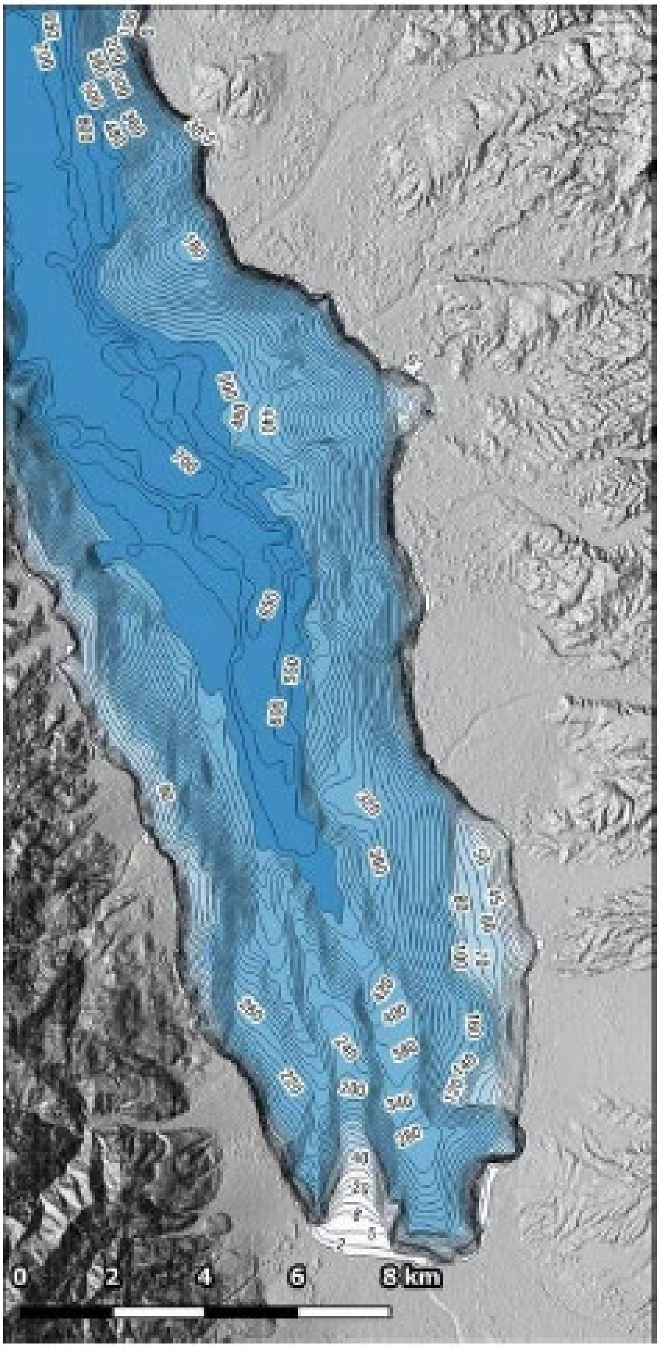

Figure 7. Badan Informasi Geospasial Contour map of Palu Bay before the earthquake, Retrieved from https://cloud.big.go.id. Accessed 30 Oct 2018.

From observations made during the mission by the EEFIT-TDMRC Team, a further possibility is a combination of vertical fault movement under Palu Bay, combined with triggered submarine landslides. It is possible that a step-over fault underlying the bay formed a contractional bend and resultant thrust faulting has led to vertical displacement of the sea bed. This was not proven by any of the bathymetric survey data available to the EEFIT-TDMRC Team at the time of the mission.

Despite causing considerable damage along the shoreline (Figure 8), the horizontal inundation of the tsunami was relatively modest. This is an indicative characteristic of landslide generated tsunamis. There was no evidence of the tsunami having travelled up the Palu river at the southern end of the bay, which is in contrast to what has been found on previous EEFIT missions e.g. Japan 2011. A possible reason for this is that the collapsed Palu Bridge IV created a barrier to the tsunami; the collapse of the bridge occurred due to the earthquake ground shaking.

Figure 8. Wani village on the east coast of Palu bay which experienced considerable damage.

Many interviews the EEFIT/TDMRC team conducted with survivors suggested that they were aware that tsunamis followed earthquakes, so they understood the importance of evacuating inland. This self-evacuation was critical to the survival of residents as the waves hit within a few minutes of the earthquake.

Structural Damage of Buildings and Infrastructure Investigation

The EEFIT-TDMRC mission made observations of the damage to buildings and infrastructure including housing, schools, hospitals, hotels and coastal defences amongst others. For the purposes of this paper observations of damage and performance of typical low-rise housing structures and schools are summarised.

Typical low-rise houses

Typical low rise construction of Palu and Donggala is here divided into three different categories: timber "stilt" houses, timber framed houses with infills and confined masonry (clay brick and concrete block) houses. These three categories of buildings represent different eras of non-engineered building practice in the city.

Traditional timber housing in Palu is two-storeys in height, where the main living quarters are on the 1st floor and the ground storey has no cladding i.e. the house is effectively on stilts. The stilt houses showed varied performance under the earthquake and tsunami. At the shore-front these structures performed badly due to ground subsidence and the tsunami inundation reaching the first floor. However, in other areas, where the tsunami inundation did not exceed the ground floor, this type of housing was seen to perform well due to their open ground floor offering little resistance to the flow.

Other timber frame houses with infills were also observed. The typical earthquake induced damage observed in these buildings was out-of-plane failure of the infill walls or separation between the infill and frame due to differential settlement.

The most common non-engineered construction observed in Palu is confined masonry (CM). Typical damage sustained by CM houses along the coast line in Palu bay area is shown in Figure 9. The main damage pattern is the out of plane failure of walls directly hit by the tsunami waves. In the case of earthquake ground shaking the weak materials used for both the masonry and confining elements resulted in out-of-plane failure of the masonry and cracking and failure of tie-columns.

Figure 9. Heavily damaged CM houses in Palu bay area along the Jl. Rajamoili road, about 100m from coastline. The walls of this house were directly hit by the tsunami inundation.

Schools

CM is also the predominant for of construction for school buildings built during the 1980s as a result of a presidential decree. Most of the CM buildings observed in the visited school compounds suffered very heavy damage, and a few buildings were seen to have collapsed. In many cases failure included damage to poorly confined heavy gables and the out-of-plane damage/collapse of long and poorly confined CM walls. The poor performance of these buildings in the earthquake was observed to be due to a number of construction defects and poor construction practices:

- Poor material quality of brick units, mortar and concrete. The latter often observed to be deteriorated and have corroded reinforcement (especially near the coast).
- Poor reinforcement detailing in tie-elements. Small rebar cross sections, very low longitudinal reinforcement ratio and large spacing of transverse ties.
- Large and poorly confined spans, which make walls vulnerable to out-of-plane failure.
- Low confinement level of thin walls (e.g. 110 mm) in both horizontal and vertical directions.
- Large and poorly confined/unconfined gables: Tie-columns in many cases not seen to extend to the full gable height, and gables are unconfined along their slopes (i.e. tie beams are absent).

In many of the observed schools, ground failure precipitated damage. Differential settlement of buildings was common in the Sigi area and areas either side of Palu bay. This may have been due to liquefaction or due to differential movement across cracks in the ground.

Some reinforced Concrete (RC) school buildings were also observed. These were 2 to 4 storey high, RC frames with brick masonry infil. These school buildings had had some level of seismic design and good material quality. Generally, reinforced concrete school buildings performed well during the earthquake ground shaking. For example, MTS Alkhairaat Pusa Palu School contained 9 two-storey RC school buildings, all of which suffered no damage. Only one 3-storeyRC building at this school complex had suffered light damage to its infill walls (Figure 11). In fact, damage to masonry infill walls was the predominant damage observed in RC frame school buildings that were subjected to earthquake ground shaking only, and an example is shown in Figure 12.

Figure 11. MTS Alkhairaat Pusa Palu School. Left – 3-torey RC frame building that sustained minor damage to infill panels. Right – Typical sizes of beams and columns in RC frame schools.

Figure 12. Damage to infill walls in a 2-storey RC school building in SD Negeri Pengawu School in Palu (Building A in Fig. 7.24).

Conclusions

A joint EEFIT-TDMRC visited Palu in the wake of the 28th September 2018 Central Sulawesi earthquake. Some of the observations made during the mission are summarised in this paper including from the geotechnical investigation, tsunami investigation and assessment of damage to buildings and infrastructure. The aim is that these observations and findings can translate to meaningful recommendations to inform development plans for the reconstruction in Palu and the surrounding area.

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